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Dynamic thermal models and CFD analysis for flat-plate thermal solar collectors – A review

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ABSTRACT

The detailed analysis of a solar collector is a complex task, due to the high number of parameters affecting its performance. In the last 40 years, several dynamic procedures have been developed and tested using numerical approaches, to obtain the behavior of the thermal solar collector without performing the set of complicated and expensive experimental tests usually adopted in steady-state approaches. Moreover, thanks to the improvement of the computing performance, these numerical models provide useful tools in reproducing for complex system behavior. In fact, when multiple energy sources are coupled together to build integrated systems (i.e., Solar-Assisted Heat Pumps, Ground-Source Solar-Assisted Heat Pump, etc.) the dynamics of each equipment has an noticeable influence on the behavior of the whole system. Therefore, these tools can be also profitably used to develop and optimize dynamic control criteria for these systems. In this context, a great effort has been made in the last years to improve the predictive potential of the dynamic models for solar collectors. Finally, thanks to the increase of the computational performance in the last years, Computational Fluid-Dynamics (CFD) approach has become a powerful tool to investigate the heat transfer phenomena. A lot of works have been made using both commercial and in-house developed codes, investigating several aspects concerning the heat transfer mechanism in a solar collector.

In the present work, an updated review of models for flat-plate thermal solar collectors is presented, including a proper classification and a description of their main characteristics and performance. A short description of the main works involving CFD analysis on thermal solar collectors is reported too.

Contents

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Nomenclature

A	area (m^2)
c_f	water specific heat ($J\,kg^{-1}\,K^{-1}$)
C_b	thermal conductance between plate and tubes ($W\,K^{-1}$)
D	tube diameter (m)
F_γ	thermal heat removing factor (–)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$I_{p,n}$	global solar radiation normal to the panel surface ($W\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
$\dot{Q}$	heat transfer rate (W)
R	thermal resistance ($K\,W^{-1}$)
T	temperature (°C)
U	transmittance, global heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)

Greek symbols

α	absorbance coefficient (–)
β	surface tilt angle (rad)
β_{PV}	cell efficiency temperature coefficient (K^{-1})
δ	thickness (m)
ε	emissivity (–)
η	efficiency (–)
η_0	electrical efficiency at standard conditions (–)
σ	Stefan Boltzmann's constant ($W\,m^{-2}\,K^{-4}$)
τ	time (s)
τ_g	solar transmission coefficient for glass windows (–)

Subscripts

e	external
f	fluid
g	glass
i	internal
p	plate
w	water

1. Introduction

Nowadays, solar thermal systems have reached a large diffusion as domestic and commercial appliances. A standard thermal solar collector can be used both for domestic hot water (DHW) production and for heating purpose. Several system configurations have been developed in the last years to reduce the energy consumption of heating systems and their operating costs. The coupling of different energy sources (i.e., solar, geothermal, electrical energy, etc.) enables the realization of integrated systems with a high thermal performance optimization which, despite the higher initial system cost, can lead to remarkable energy savings, if compared with standard heating systems [1]. A first example can be found in the photovoltaic hybrid solar panel (PV–T), which permits the production of both electrical and thermal energies by coupling a photovoltaic solar panel with a set of tubes with cooling purpose (a detailed review of these systems can be found in [2,3]). Two different goals are achieved: (i) thermal energy can be produced and used for heating purposes and (ii) a lower working temperature of the solar cells is obtained and, consequently, the electrical conversion efficiency is increased. In the last years, new techniques have been investigated in order to increase the performance of the PV panels. As an example, it is possible to keep low the cell temperature by using phase change materials which can absorbe (or discharge) a large amount of energy during phase changes [4,5]. Moreover, the use of nanoparticles within the working fluids (nanofluids) permits to enhance the heat transfer, therefore increasing the thermal performance of the collector [6]. A further technique can be found by coupling the PV-panel to the evaporator of a heat pump, thus realizing a photovoltaic solar-assisted heat pump [7]. In this way it is possible to keep low the panel temperature and, in the same time, to provide the user with high temperature thermal energy.

Generally, several high performance system configurations have been developed: Solar-Assisted Heat Pumps (SAHP), Ground-Source Solar-Assisted Heat Pump (GS-SAHP) and Photovoltaic Solar-assisted Heat Pump (PV-SAHP). Ozgener and Hepbasli [8] and Ji et al. [9] described various plant arrangements in which solar collectors (both photovoltaic and thermal) can be coupled with heat pumps and geothermal storage. In all these configurations, the dynamic characteristics of each component have a strong influence on the short term thermal performance of the whole system. A careful design must involve a control strategy analysis to optimize energy savings during operation. In particular, the behavior of the solar collector, which is heavily influenced by the very quick variation of the external conditions during daytime (mainly due to solar irradiation), affects the working conditions and thus the performance of the system. Therefore, the understanding and the ability in predicting the dynamic behavior of solar collectors can give a strong incentive to develop suitable and optimized regulation strategies, especially when the collectors are directly coupled with other devices.

Moreover, a numerical model able to reproduce collector dynamic behavior represents a useful tool in order to perform more reliable external tests then those required by the usual standards [9–11], thus resulting in reduced execution time and costs.

To this end, several numerical models have been developed in the last years to describe the dynamic thermal behavior of flat-plate thermal solar collectors. Stepping from the early work by Smith [12], the main procedures adopted to model flat-plate thermal solar collectors are reported and analyzed in this paper. A list of the main works on this topic is reported in Table 1.

Since most of these models have been developed to obtain better external test procedure, a list of the main references about these testing procedures is given too. Finally, since during the last ten years, several computational fluid-dynamic analyses (CFD) of the thermal solar panel have been performed, a short description of these works is reported too, to complete and update the early review by Schnieders [13].

2. Steady state approach

The governing equations describing the phenomenon, based on the conservation of physical quantities (mass, momentum and

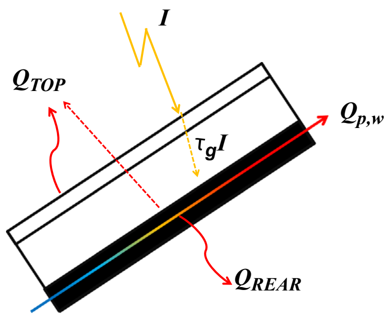

Fig. 1. Energy balance of a thermal solar collector in steady state.

energy), are simplified to obtain a simple set of equations featuring a low computational cost. Hottel and Woertz [14], Hottel and Whillier [15] and Bliss [16] developed the simplest assumptions: thermal capacitances are neglected and a single value of collector overall heat loss coefficient is considered, which depends on collector characteristics (geometry, mass flow rate, efficiency itself, etc.), average plate temperature and external conditions (air temperature and external heat transfer coefficient). Based on these assumptions and considering that the heat transfer is mainly one-dimensional and predominant in the direction normal to the flow plane, Duffie and Beckman [17] developed a simplified model to characterize the solar collector in steady state adopting the electrical analogy. Neglecting the thermal capacitances (Fig. 1), the temperatures of absorber, back plate and covers are calculated using an energy balance equation. The steady-state model is the most used for calculating the thermal performance of solar collectors but, for calculation purposes, it is suitable only when long time averaged weather data (e.g., monthly) are considered. Moreover, the requirement of steady state conditions makes experimental tests on collectors more complicated and expensive.

3. Dynamic models

3.1. Lumped-capacitance model

The first attempt to implement a dynamic numerical model was made by Close [18] who took into consideration a lumped thermal capacitance located on the collector plate, which represents the sum of the thermal capacitances of various elements (like fluid, plate, glass covers, etc.). It is called 1-*point lumped model* and it consists of one energy balance differential equation based on the steady state scheme shown in Fig. 1, which can be written as follows:

$$c_p \frac{\partial T_p}{\partial \tau} = (\alpha\tau)_p A_p \dot{I}_{p,n} - \dot{Q}_{loss} - \dot{Q}_{p,w} \tag{1}$$

where c_p and T_p are the lumped thermal capacitance of the overall solar collector and its temperature respectively and $(\alpha\tau)_p$ is the product between the glass transmittance τ and the plate absorbance α.

$\dot{Q}_{loss}$ and $\dot{Q}_{p,w}$ are the global heat loss and the useful heat transferred to the fluid respectively. They can be calculated adopting the steady state formulation given by [15,16]

$$\dot{Q}_{p,w} = F_r A_p [(\alpha\tau)_p \dot{I}_{p,n} - U(T_{f,in} - T_e)] = \dot{m}_f c_f (T_{f,out} - T_{f,in}) \tag{2}$$

$$\dot{Q}_{loss} = U A_p (T_p - T_e) \tag{3}$$

The term F_γ in Eq. (2) is the thermal heat removing factor [17,19], while the term U_c, appearing in Eqs. (2) and (3), represents the overall heat loss coefficient between plate and air which can be calculated as

$$U = U_{TOP} + U_{REAR} \tag{4}$$

where U_{REAR} is the rear heat loss coefficient which normally can be considered constant and equal to the reciprocal of the thermal resistance of the insulation. U_{TOP} takes into account both convection and irradiation in the top of the solar collector and it can be calculated as suggested by Klein [20]

As well known, the main performance parameter of a solar thermal panel is the collector efficiency defined as the ratio of the collected thermal power over the total incident solar power:

$$\eta_{sc} = \frac{\dot{Q}_{p,w}}{\dot{I}_{p,n} A_p} = F_r (\alpha\tau)_p - \frac{U(T_{f,in} - T_e)}{\dot{I}_{p,n}} \tag{5}$$

A full description of the theoretical calculation and the assumptions required to obtain the previous model can be found in [21]. The main limitation of this model is that it cannot reproduce the spatial temperature profile inside the collector, therefore it causes errors in heat losses calculation and, consequently, in the outlet water temperature results.

Separating the thermal capacitance of the covers from the global thermal capacitance, Wijeysundera [22] developed a 2-*point lumped model*, in which the solar collector is modeled as two-region: (i) the absorber plate and the heat removing fluid, and (ii) the cover plates lumped together in a single equivalent cover. The comparison of this approach with the 1-*point lumped model* showed that the outlet fluid temperature variation is overestimated by the 1-*point model* and it is underestimated by the 2-point model. Moreover, analyzing the influence of the thermal capacitance on the long term behavior of the solar collector, the author showed that the steady state approach gives good results in predicting the daily energy collection only when hourly averaged meteorological data is used. If the radiation intensity changes quickly, the dynamic effects become most pronounced and the steady state model overestimates the useful energy collection. In these conditions transient approaches provide better results. The author concluded that the main usefulness of the dynamic approach in modeling the solar collector is detected in the short term study and in predicting the outlet temperature behavior as a consequence of the fluctuations of the climatic data.

Morrison and Ranatunga [23] developed a 3-*point lumped model* separating the thermal capacitance of the fluid and the absorber, realizing a set of three equations: cover, collector plate and fluid. Moreover, the authors take into account the thermal capacitance of each section of the water loop tubes between the solar collector and the tank, considering the fluid acceleration during the transient heating. The authors used this approach in order to analyze the response of a thermosyphon solar water heater to step changes of insolation.

A recent application of this model can be found in [24], who developed a single-capacitance lumped model with the aim of optimizing a solar thermal flat-plate collector. The model showed a good agreement with experimental data. On the same bases, Fraisse et al. [25] proposed a model based on a simplified electrical analogy, taking into account the temperature-dependency of thermo-physical characteristics of the collector. Authors introduced the lumped thermal capacitances for glass cover, absorber and fluid (developing a 3-*point lumped model*). Three different energy balance equations have been written and solved in transient state. The model was compared to outdoor experimental data set and the results obtained by the well-known software TRNSYS®. Such comparison showed a good agreement between numerical and experimental results, except for the stagnation period. Authors highlighted the importance of the transient approach when the time step is small and the water loop working is intermittent. While the fluid thermal capacity is included in c_f (Fig. 2), the possibility to calculate the fluid outlet temperature is

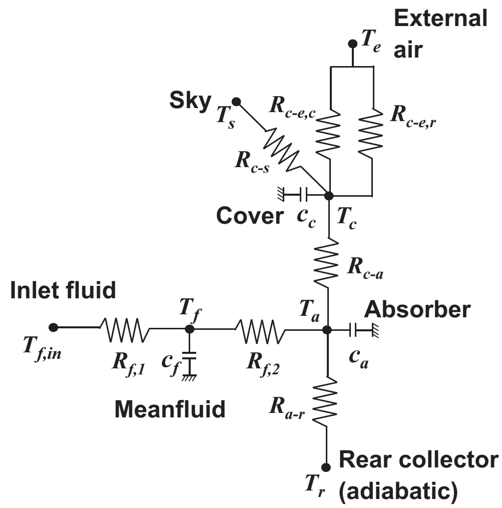

Fig. 2. Electrical network of the solar collector adopted by Fraisse et al. [25] (adapted).

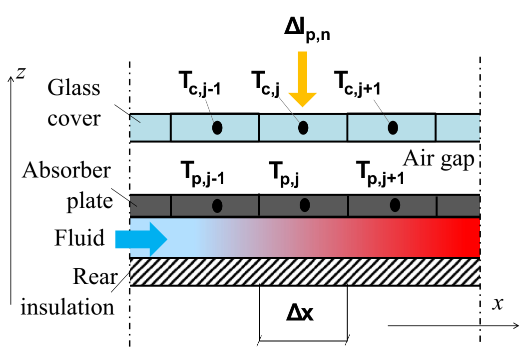

Fig. 3. The basic 1*n-node* schema with $T_{p,j}$ is extended with further 1*n-node* with $T_{c,j}$ on the collector glass cover, realizing a 2*n-node* model.

obtained introducing a temperature difference $T_f - T_{f,in}$ across the thermal resistance R_{f1} with steady-state thermal balance.

Taherian et al. [26] adopted a 2-point lumped model taking into account the thermal capacitance of cover and absorber plate for closed thermosyphon water heater. The comparison between simulation results and experimental data confirms that the lumped capacitance approach is capable of predicting the system efficiency accurately only with sunny conditions, while in cloudy days it does not provide accurate results.

3.2. Discretized model

Klein et al. [27] modified the lumped model considering the fluid temperature variation along the solar panel. In their approach, the collector is discretized along the fluid flow (x-direction) and an unsteady energy balance equation is written for each node. This method is called "*one-node capacitance model*", or "1*n-node model*". Furthermore, authors suggested to add other node-points positioned at the collector single glass cover.

De Ron [28] developed a dynamic solar collector model considering that the heat transfer conduction between fluid and the absorber is essentially 1-D and perpendicular to the flow plane. Collecting the suggestion by Klien et al. [27], the author developed an ordinary time-differential energy balance equation for cover and absorber plate, assuming that (i) the heat capacity of the air gap between the cover and the absorber plate is negligible and (ii) the collector rear and edges are adiabatic. Therefore, this model it is called "2*n-node model*" because both the thermal capacitances of the plate and of the glass cover are taken into consideration (Fig. 3).

Kamminga [29] took into account the thermal capacitance of the fluid as well, together with the cover and the absorber plate thermal capacitances, developing a "3*n-node model*". The solar collector is modeled as a single channel in which the fluid flows with a velocity u in the x-axis direction. The heat transfer along the flow direction is due only to the fluid motion (conduction is neglected) while the heat transfer along z-axis is described by the electrical analogy, as shown in Fig. 4. Moreover, adding the thermal capacitance of the rear thermal insulation, a "4*n-node model*" was achieved. These models result in a set of linear partial differential equations (PDEs) which can be simplified and solved by transforming them into ordinary differential equations (ODEs) and using a robust numerical method, such as the 4th order Runge–Kutta method [30]. Nevertheless, the implementation of the 3n and 4n models results in high computational costs and, for this reason, often the 2n model was preferred to reduce the number of differential equations.

Oliva et al. [31] developed a numerical method based on a multidimensional modeling of the solar collector components (glass cover, tubes, insulation, etc.) which have been applied on an air collector with rectangular ducts. Starting from the previous works, authors implement a 4*n-node model* taking into consideration the thermal inertia of major components (glass cover, tubes, internal fluid and insulation) and adopting a two-dimensional approach for the glass cover and the ducts and a three dimensional geometry for the insulation. Moreover, the fluid temperature distribution is calculated by solving the Navier–Stokes equation with a finite volume approach in one-dimensional geometry, while the air gap between the glass cover and the tubes is modeled with empirical expressions. This model is physically rigorous and shows a good performance but it is hard to be implemented and it requires a high computational burden and could be excessively slow in a modern optimization/real-time control strategy use.

In [32–34] a parameter identification technique (DFA, dynamic fitting algorithm) is used developed by Spirkl [35,36] to identify the main parameters (effective collector area, collector heat capacity, heat loss coefficient, etc.) of the solar collector, applying a best fit procedure on experimental data (dynamic fitting algorithm). The collector is split into units and an energy conservation equation is solved for each of them to calculate fluid temperature. This method has been developed in the framework of dynamic test procedure for domestic hot water solar collectors and may be considered as a 1-*node* model. The method showed an accurate

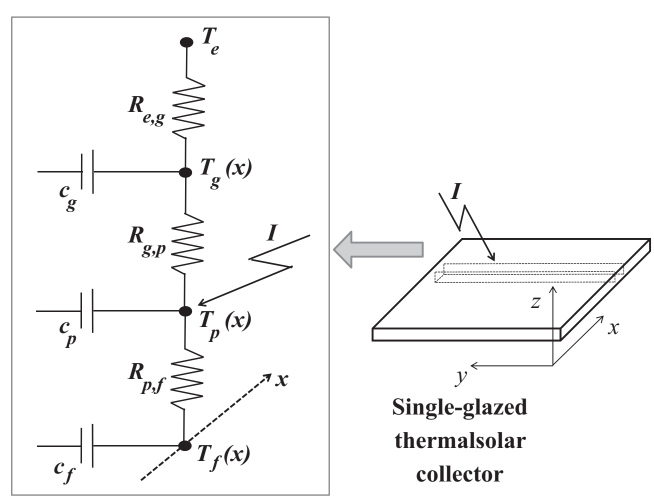

Fig. 4. Electrical analogy of a 3n-nodes model of a solar thermal collector.

performance, especially for double-glazed collector in short time tests, with a low computational time thanks to the assumption of an identical temperature for both fluid and absorber.

Schnieders [13] analyzed the performance of a vacuum tube solar collector comparing the stationary model to five dynamic approaches based on the previously described models (for further details of the different 1-*node* approach, refer to the corresponding references): 1-*point lumped*, 1-*node MFC* [37,38], 1*n*-*node DSC* [32], 2*n*-*node* and 3*n*-*node*. The study showed that the best results were achieved by the 2*n*- and 3*n*-*node models* with similar behavior when a low value of $R_{g,p}$ is given. The author showed that for constant inlet temperature and with low values of the flow rate, all the models predict the daily energy yield with low discrepancies. In these operating conditions the 1-*point model* appears to be preferable due to its low computational effort. Furthermore, the author highlights that the 1-*point* and the stationary models can predict the daily energy yield only if the variations of solar radiation are smooth during the day. Moreover, the 1-*point model* is able to predict the system behavior only for constant inlet temperature and if the time step is greater than the variation time scale of the collector. Finally, the author concluded that additional errors may occur for both 1-*point* and stationary model if the solar collector is coupled with other components, which are strongly influenced by the time dependence of the operating conditions.

Hilmer et al. [39] presented a model to evaluate the short-term dynamic behavior of unglazed solar collectors installed on the roof at various flow rates. The authors investigated the effect in predicting the dynamic behavior of the solar collector due to the introduction of the roof thermal capacitance in the model. The application of the method to a large unglazed collector for swimming-pool heating showed a good accuracy, highlighting that the introduction of the roof thermal capacitance yields the best results for short-term collector behavior. Instead, the simple-capacitance model can achieve good results also for strongly varying flow rates to obtain hourly mean values of the useful energy gain delivered by the collector.

Cadfalch [40] presented a detailed numerical approach which can be considered as an extension of the 1*n*-*nodes dynamic model* developed by [17]. Starting from the assumption that the heat transfer phenomena which occur in a solar collector are essentially 1-D (the edge effects are not taken into account), the 1-D domain is discretized in different layers, and each one is characterized by three parameters to take into account the heat transfer, the thermal inertia and the absorbed energy. The number and type of the layers included in the model depend on the components that configure the solar collector, while the evaluation depends on the used model (1*n*, 2*n*, etc.). The model was verified against experimental data for a single and a double glazed collector operating in steady state conditions.

Starting from the multidimensional model by Oliva et al. [31], Villar et al. [41] developed a transient 3D model for solar flat plate collectors, based on mass and energy finite volume balance equations, to investigate the different internal tubes configurations. The model takes into account the multidimensional and transient character of the problem, allowing the calculation of the spatial dependence temperature of the components (glass cover, absorber plate, fluid and rear insulation). In this way, a 4*n*-*nodes 3D model* is developed and validated experimentally using a commercial thermal solar collector in steady state conditions. Moreover, authors investigated the effect of flow non uniformities on the collector efficiency.

Zima and Dziewa [42] proposed a one-dimensional mathematical model taking into account only the thermal capacitances of the fluid and the tube (Fig. 5). Authors obtained two ordinary differential energy equations which are characterized by two distributed temperature-dependent parameters. The first of them represents the time constant due to inertia, while the second one takes into account the heat transfer characteristic and the relation between the fluid heat capacity and the thermal power on the surface. The model is discretized and solved using an implicit finite difference method. The validation of the model was performed comparing its results with those obtained by known analytic solutions for transient operating conditions. An extension of this model is shown in [43], where the authors extend the analysis of the inertia effects to cover, air gap and back insulation, by means of one-dimensional 5*n*-*node model*.

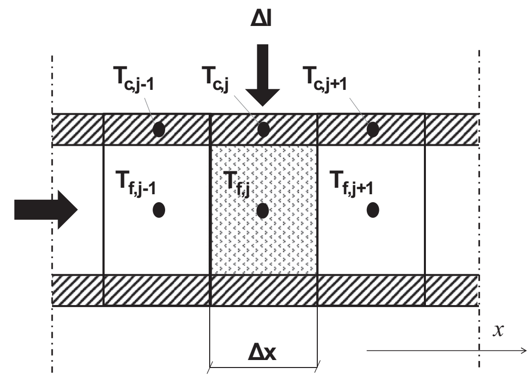

Fig. 5. Control volume of the solar collector tube (adapted from [42]).

3.3. Model comparison for performance and effectiveness

All the described models have been analyzed and compared by different authors in order to understand their predictive capabilities, principally in terms of outlet and mean water temperatures and energy yield. The present paragraph shows an overview of the main information collected over the years, highlighting, in particular, the most suitable application for each approach.

- Steady state model: neglecting the thermal capacitance, this approach is able to give accurate results only with long-time averaged data, as highlighted by [13,22]. Its simplicity and computational efficiency makes this approach useful to perform long-time simulations in a preliminary study perspective, while it is not suitable for achieving control criteria for instantaneous regulation systems.
- Lumped capacitance models: they represent the fastest and simplest dynamic models that permit to introduce inertia effects by considering global thermal capacitances. Comparisons with experimental data have shown that this approach is able to give accurate results in predicting the energy yields only with low inertia effects or, in other words, if the variable input fluctuations (such as solar radiation, air and inlet temperatures) are small. As a reference, Fig. 6 provides the comparison between simulation results and experimental data for a sunny and a partly cloudy day obtained by Taherian [26]. In particular, it is clear that when the solar collector is subjected to higher variations of the climatic conditions (partly cloudy days), the model is not able to correctly predict the outlet temperature as when constant solar irradiation is present (sunny days). In fact, if the input variables change rapidly (especially, the inlet water temeprature and the solar irradiation) the inability to reproduce the spatial profile of the flowing fluid causes errors in the fluid outlet temperature calculation.

  Generally, this approach appears to be reliable for constant water inlet temperature and if the simulation time steps are suitably smaller than the characteristic time scale of the collector. Adding capacitance node for cover [26] or for cover,

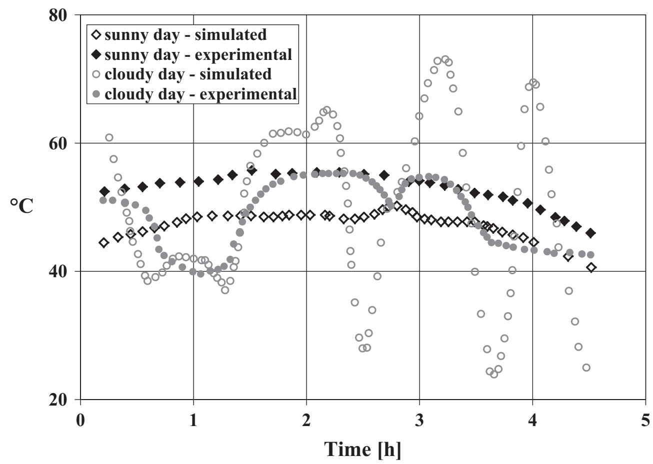

Fig. 6. Comparison between the increase of the fluid temperature for a sunny and partly cloudy day (adapted from [26]).

absorber and fluid [25] permit to increase the model accuracy, althought with a more computation efforts. Testing procedure for solar collector, simulation tools for predictive purpose in the early stage design and simple control criteria (e.g., based on misured solar radiation) can be excellent application areas for this approach.

- Discretized model: introducing the discretization of the solar collector along the fluid direction, it is possible to reproduce the fluid temperature profile and, therefore, to calculate the outlet fluid temperature with a higher accuracy. Adopting a unique global thermal capacitance for each axial node (1*n*-nodes) the heat transfer inside of the collector is lost, producing a worse description of collector inside dynamics. By separating the thermal capacitance of cover, absorber and fluid permits to reproduce well the inertia effects, despite a higher computational costs and a more complex implementation. Notwithstanding, Schnieders [13] has demonstrate that the prediction of the total daily energy yield provided by more complex model (1*n*-nodes to 3*n*-nodes) is nearly the same, while the outlet fluid temperature can be quite different. This consideration is essential in a optimization perspective, considering that the outlet temperature is often taken as reference of the control criteria.

These approaches are recommended if solar collectors are subjected to strong variation of the operating conditions (user demand, climatic data, etc.) due their more accurate description of the solar collector. Thanks to the increase of the computer performance in the last years, these models can be used efficiently in outdoor in situ solar collector testing and in implementation of control criteria. Generally, a more rigorous model in 2D and 3D geometries, i.e. [41], could be difficultly implemented and unsuitable in regulation control system, due to their higher computational costs. On the other hand, the more accurate description of the heat transfer inside the solar collector makes these complex approaches useful in order to optimize component design and construction.

4. Notes on the different types of flat-plate solar collector

4.1. Evacuated thermal solar collector (ETSC)

Evacuated heat pipe solar collectors consist of a heat pipe inside a vacuum-sealed tube which reduces convection and conduction losses permitting to operate at higher temperatures than the standard flat-plate solar collector. Different methods can be adopted to extract heat collected by the absorber, according to the collector configuration as reported by Morrison [44]. Generally, if a single vacuum tube is adopted, a metal absorber is mounted inside at the greater diameter and a U-shape tube with the heat removing fluid is welded on it. According with the collector dimensions, the removing fluid can be water or air. Otherwise, two concentric tubes can be mounted and the vacuum is realized in the space between them (Dewar tubes). The solar absorber surface is generally realized in the vacuum side of the inner tube and the absorbed heat is extracted by the removing fluid flowing in the inner tube.

Moreover, ETSC can use liquid–vapor phase change materials to transfer heat at high efficiency [21,45]. These collectors consist of a vacuum tube in which a sealed heat pipe evaporator is introduced. A protrusion in the heat pipe top, the heat pipe condenser, is inserted in the manifold exchanging heat with the removing fluid. The heat pipe is filled by a small amount of fluid which evaporates under the effect of the solar irradiation and, therefore, flowing in the condenser in which it condenses exchanging heat with the removing fluid.

Several studies investigated the thermal performance of ETSCs. A steady state approach has been adopted by [46–51]. In particular, [46,47] adopted a steady state one-dimensional discretized model in order to predict the thermal performance of the solar collector under steady-flow conditions.

Several studies have been performed in order to investigate the influence of the collector characteristics on the ETSC thermal performance. Shah and Furbo [48] developed a theoretical model adopting the steady state assumption to analyze the thermal performance of vertical evacuated collectors. The model has been validated with outdoor test results showing a good performance. Several studies have been performed at different North locations in order to investigate the optimum tube distance configuration and collector azimuth.

Ma et al. [49] and Badar et al. [50] adopted a one-dimensional analytical steady state approach in order to investigate the overall heat loss coefficient of a single unit of vacuum tubes with coaxial conduit and a glass evacuated tube solar collector with U-tube respectively. Badar et al. [51] extended their researches introducing a system of equations which describes the different heat transfer mechanisms and flow conditions adopting both single and two-phase flow description. The authors showed that for all-liquid-single-phase fluid flow, the collector efficiency decreases with decreasing mass flow rate, while if the boiling point at a certain mass flow rate is reached no efficiency reduction is observed.

Budihardjo and Morrison [52] performed several simulations using TRNSYS in order to investigate the performance of water-in-glass evacuated solar water heaters with water tank. Analyzing different models provided within the TRNSYS environment, authors investigated the effect of several parameters (tilt angle, locations, system size, tank size, etc.) considering the inertia of the thermal storage.

As previously mentioned, a great effort in analyzing and comparing the different performance of dynamic models applied to ETSC was made by Schnieders [13] who compared different dynamic approaches (see Section 3.2). Starting from this work and collecting the mathematical description made by Kamminga [29], Praene et al. [53] performed several simulations using a 3*n*-nodes model in order analyze the thermal performance of a ETSC. Comparing numerical results with experimental data, the model showed a good accordance with the measurements.

Ayompe et al. [54] developed a TRNSYS model for forced circulation heating system with flat plate and heat pipe evacuated

tube collectors in quasi-dynamic conditions. Results showed that TRNSYS model predicts the outlet water temperature with errors lower than 20%. Authors stated that this model can be profitably used to predict long-term performance of the solar water heating system in different locations and with different operating conditions. With the same approach, Chow et al. [55] performed several TRNSYS simulations of two different configurations of ETSC (single and two-phase flow design) for DHW applications. Adopting a lumped capacitance approach for fluid and absorber (2-point), the model has been validated comparing results with experimental data collected in Hong Kong.

4.2. Photovoltaic Hybrid solar panels (PV–T)

Photovoltaic hybrid solar panels (PV–T) permit the production of both electrical and thermal energies by coupling a photovoltaic solar panel with a set of tubes with cooling purpose. Thanks to the lower working temperature of the solar cells, the electrical conversion efficiency is increased with a production of thermal energy which can be used for heating purpose. A detailed review on these systems can be found in [2,3]

The steady state thermal efficency of the PV–T panel can be calculated adopting the same approach used for the standard flat plate thermal solar collector (see Section 3.1) considering the temperature dependency of PV module electrical efficency on PV module temperature given by the following equation [56]:

$$\eta_{el} = \eta_0(1 - \beta_{PV}[T - T_{ref}]) \tag{6}$$

Zondag et al. [57] developed four numerical models in order to simulate the thermal yield of a PV–T solar collector. In particular, authors analyzed a 3D dynamic model with three different steady state approaches in 3D, 2D and 1D, comparing their results with experimental data. Results showed that all models predict the daily energy yield with accuracy within 5%. Moreover, authors stated that 2D and 3D models permit to obtain more information about the panel operating conditions, making them more flexible and adaptable to more complicated panel design despite a greater computational cost.

4.3. Solar collector with nanofluids

In recent years the idea of adopting nanoparticles within the working fluid has been investigated by several researchers. Studies focused on the effect of nanoparticle on the thermo-physical properties of the fluid and to investigate the heat transport capability of nanofluids have been conducted, e.g. [58–61]. The innovation provided by the use of nanofluids is connected with the heat transfer enhancement which can be obtained and regards a lot of industrial sectors, including power generation, chemical and metallurgical sector, heating and cooling systems, refrigeration systems and so on [62]

The application of nanofluids in solar energy has been analyzed related essentially to solar collectors, highlighting both energy, economic and environmental aspects [63–65]. As for instance, Yosephi et al. [66] showed that using Al_2O_3 nanofluid in a flat-plate solar collector can increase its efficiency until 28.3%. The effect of adopting different types of particles has been analyzed by Otanicar [67]. Moreover, the effects of several parameters affecting the enhancement of the solar collector performance have been investigated [62,68,69].

A recent detailed review can be found in Mahian et al. [6] in which the authors report an exhaustive description of the different applications of nanofluids in solar energy field.

The numerical analysis of these particular types of solar collector is generally performed solving the governing fundamental equations with CFD software packages due to the necessity to correctly describe the fluid flow inside the collector. Recently applications of CFD to model nanofluids were reviewed by Kamyar [70].

5. Artificial neural network models

The technique called Artificial Neural Network (ANN) can be applied in different applications (e.g., medicine, control, robotics, power system, signal processing, optimization), especially in the case when the implementation of a complex mapping and system identification are needed. ANN consists of a “black box” model [71] which does not require detailed information about the system because it can learn the relationship between the input parameters and the variables by analyzing the previously recorded data. A neural network architecture is created by a collection of small individual processing units (as neurons) which are crossed by information and connected each other by an adaptable connection layout (Fig. 7).

Kalogirou [72,73] provided a detailed review of ANN applications in energy systems, reporting several examples of uses for different purposes (i.e., solar steam generator, solar water heating system, photovoltaic system, solar radiation and wind speed, building thermal load, refrigeration, tariff forecasting and energy management, etc.). He showed that this method has been applied in a wide range of fields for modeling and prediction in energy.

The first investigation of the ANN technique capability in predicting the thermal performance of a thermal solar collector was made by Kalogirou et al. [74], who investigated a solar DHW system obtaining results with prediction errors less than 10% from experimental data. Authors identified the main advantages of this approach, compared with the standard algorithms in terms of (i) speed calculation, (ii) simplicity and (iii) learning capability from available data. Moreover the authors identified the main disadvantage of the method in the inability to understand the correlations among each different parameter, thus making the causes of a “low reading” of the thermal performance difficult to be understood.

Lecoeuche and Lalot [75] performed an application of the ANN technique to predict the daily performance of solar collectors, showing that neural networks can model the solar collector very well (also in comparison with other methods), with a discrepancy lower than 0.5%.

Kalogirou [76] developed six ANN models to predict the standard thermal performance collector equation parameters, both in no-wind and wind conditions, taking into account the

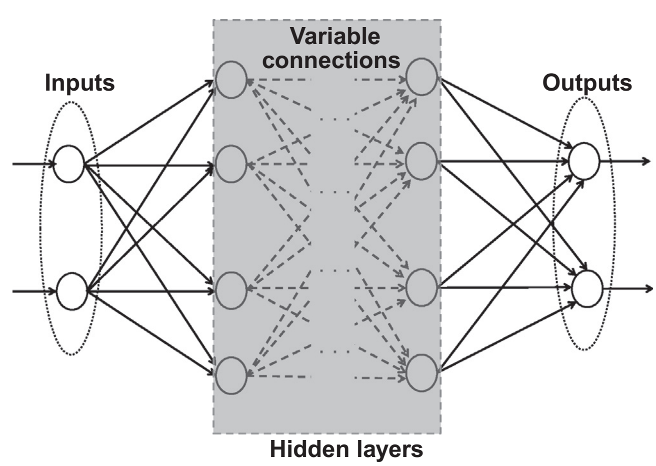

Fig. 7. Conceptual diagram of a multilayer artificial neural network (adapted from [73]).

Table 1
List of the main works on the dynamic models for solar thermal collector. Reviews available before the present paper: Smith [12], Schnieders [13], Kalogirou [73] (ANN).

Year	Author/s	Type of model	Geometry	Description
1942	Hottel and Woertz	Static	–	Thermal capacitance is neglected and an overall heat loss coefficient is considered
1955	Hottel and Whillier	Static	–	
1959	Bliss	Static	–	
1967	Close	Dynamic	Lumped	1-point-lumped model
1974	Klien et al.	Dynamic	1D	1*n*-nodes model
1978	Wijeysundera	Dynamic	Lumped	2-point-lumped model
1980	Morrison and Ranatunga	Dynamic	Lumped	3-point-lumped model
1980	De Ron	Dynamic	1D	2*n*-nodes model. Thermal capacitances: glass cover and plate
1985	Kamminga	Dynamic	1D	3*n*-nodes model. Thermal capacitances: glass cover, plate, and fluid 4*n*-nodes model. Thermal capacitances: glass cover, plate, fluid and rear insulation
1986	Smith	Static/ dynamic	–	Review and comparison of the main dynamic models [12]
1991	Oliva et al.	Dynamic	2D/3D	multidimensional 4*n*-nodes model. Fluid 1D, cover and duct 2D, insulation 3D. Air gap modeled using empirical correlation
1991	Duffie and Beckman	Static	–	Steady state analysis with electrical analogy
1993	Muschaweck et Spirkl	Dynamic	1D	DSC: dynamic test procedure based on a 1*n*-node model with DFA technique [35] to identify the parameters
1994	Bosanac et al.			
1997	Spirkl et al.			
1997	Schnieders	Static/ dynamic	–	Comparison of the main dynamic models in terms of energy yield predictions [13]
1999	Hilmer et al.	Dynamic	1D	2*n*-nodes model for unglazed collectors installed on a roof. Thermal capacitances: plate and roof
1999	Kalogirou	ANN	Any	Artificial Neural Network Model for DHW solar thermal collector
2000	Kalogirou			
2001	Kalogirou	ANN	Any	Review of the ANN applications in solar systems [73]
2003	Fraisse et al.	Dynamic	Lumped	3-point-lumped model. Thermal capacitances: glass cover, absorber and fluid.
2003	Al-Ajlan et al.	Dynamic	Lumped	Single capacitance lumped model.
2005	Lecoeuche and Lalot	ANN	Any	Artificial Neural Network Model – Testing in different conditions
2009	Cadafalch	Dynamic	1D layers	Extension of 1*n*-nodes model by Duffie and Backman [17].
2009	Villar et al.	Dynamic	3D	4*n*-nodes model. Thermal capacitances: glass cover, plate, fluid and rear insulation. Mass and energy finite volume balance equations for fluid.
2010	Zima and Dziewa	Dynamic	1D	2*n*-nodes model based on two ODE characterized by temperature-dependent parameters which modelling the heat transfer characteristic and the inertia
2011	Zima and Dziewa	Dynamic	1D	Extension of 2*n*-nodes model by Zima and Dziewa [42] to take also into account the inertia of cover, air gap and back insulation (5*n*-nodes).

wind incident angle, the collector time constant, the stagnation temperature and the collector thermal capacity. The accuracy showed by the models was good and the author concluded that the model performance could be improved by using it, thanks to the ability of the ANN to learn from new examples (e.g., during operation).

6. Notes on the test methods for model assessment

Several test methods with different procedures have been developed to assess the solar thermal collector performance. Such methods can be divided into two groups: the steady state and the dynamic test method. A comparison between these approaches is reported in Table 2, adapted from [77]. The steady state test method is the usual procedure adopted by most of the common standards such as [9–11]. Indoor tests are often expensive and can be conducted in certified laboratory with a solar simulator, while outdoor procedures require specific ambient (environmental and climatic data) conditions. Moreover there are often discrepancies between indoor and outdoor results, probably due to errors in describing the sky temperature in the indoor tests.

To solve these difficulties and to reduce the cost of the tests, a dynamic test procedure is suggested. Actually, only the standard [11] considers a "quasi-dynamic test method" (for details, see [78–80]). Nevertheless, a lot of dynamic test procedures have been proposed, most of them based on the dynamic numerical models described in previous paragraphs.

Table 2
Comparison between steady test method and dynamic test method (adapted from [77]).

Main characteristics	Solar panel test methods	
	Steady state	Dynamic
Mathematical model	Simple	Relatively complex
Data processing	Convenient calculation	Relatively complex data processing
Test condition	Given weather condition	Variable/totally dynamic weather conditions
Parameter permitted deviation	Restricted	Relatively loose
Test period	Long test period	Relatively short test period
Adaptability	Limited	Relatively extensive

These different procedures are not analyzed in the present work, for a detailed literary review with a properly classification see [81] and, more recently, [82,83].

7. CFD analysis

Thanks to the improved computational capabilities achieved by computers in the last years, a lot of authors have performed several numerical CFD simulations using commercial simulation tools, devoting a great effort to the description of the behavior of solar collectors.

In order to analyze the flow distribution inside a solar collector with horizontal inner tubes, Fan et al. [83] compared the

experimental data obtained by several outdoor tests, with the CFD calculations performed using Fluent 6.1®. The collector is modeled assuming a uniform energy generation in the absorber tube and considering only a convective heat loss coefficient, calculated using external software SolEff® and set as an input for the CFD calculations. The comparison between the numerical results and the experimental data showed a good agreement in case of high flow rates, while some discrepancies appears at low flow rate. In the author's opinion this is due to the oversimplification of the collector model especially inside the air gap of the panel. Moreover the authors showed non-uniformity in the mass flow rate distribution with the horizontal configuration of the tubes, due to the effect of the buoyancy, especially with low mass flow rates. This non-uniformity rises with the increase of the tilt angle and of the inlet temperature, and can cause a decrease of the solar collector efficiency, with increased risks of local boiling.

Selmi et al. [84] simulated a flat-plate solar collector in 3D geometry using the commercial CFD software CFD-ACE+® [85] the numerical results are compared with experimental data, showing good agreement in the temperature profiles.

An experimental and numerical analysis was conducted by Turgut and Onur [86] to determine the average heat transfer coefficients for forced convection air flow over a flat plate solar collector surface. The authors started from the work made by Sartori [87], who demonstrated that the most commonly used equation for the calculation of heat transfer coefficient [17,88,89], depending only on wind velocity, are in contrast with the boundary layer theory and does not correctly represent the convective heat transfer over the plate. In this context they performed an experimental study with the aim of providing a dimensionless empirical correlation for convective heat transfer at different panel tilt angles and wind velocities, based on experimental data. Moreover, using the commercial CFD software Fluent 6.3®, the same authors performed several numerical simulations and compared them to experimental results, showing a good agreement in predicting the heat transfer coefficient ($\pm$12% variance).

Karanth et al. [90] adopted the Discrete Transfer Radiation Model (DTRM) inbuilt in Fluent 6.3®, to model the radiation heat transfer and the solar radiation. The panel is made of a set of parallel channels in which a one-through water mass flow rate is used to cool the absorber plate. Using a 3D computational domain (Fig. 8), many numerical simulations were performed, highlighting that the temperature profiles of the absorber plate and of the water flowing inside the tubes show similar linear trends with all of the different flow velocities simulated (Fig. 9). An extension of this work was made by Manjunath et al. [91], in which the same approach has been applied to an unglazed solar flat plate collector and by Manjunath et al. [92] in which different surface geometries of the absorber plate were investigated.

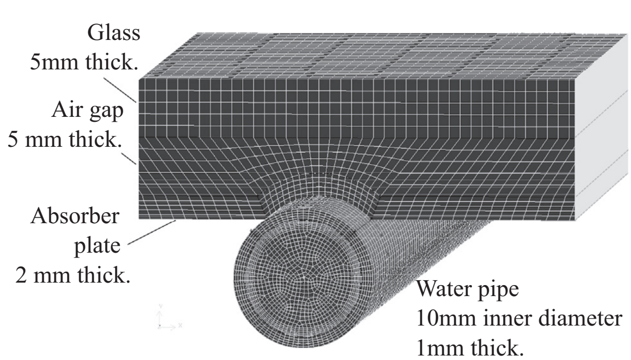

Fig. 8. Mesh for the flat-plate solar collector adopted by Karanth et al. [1].

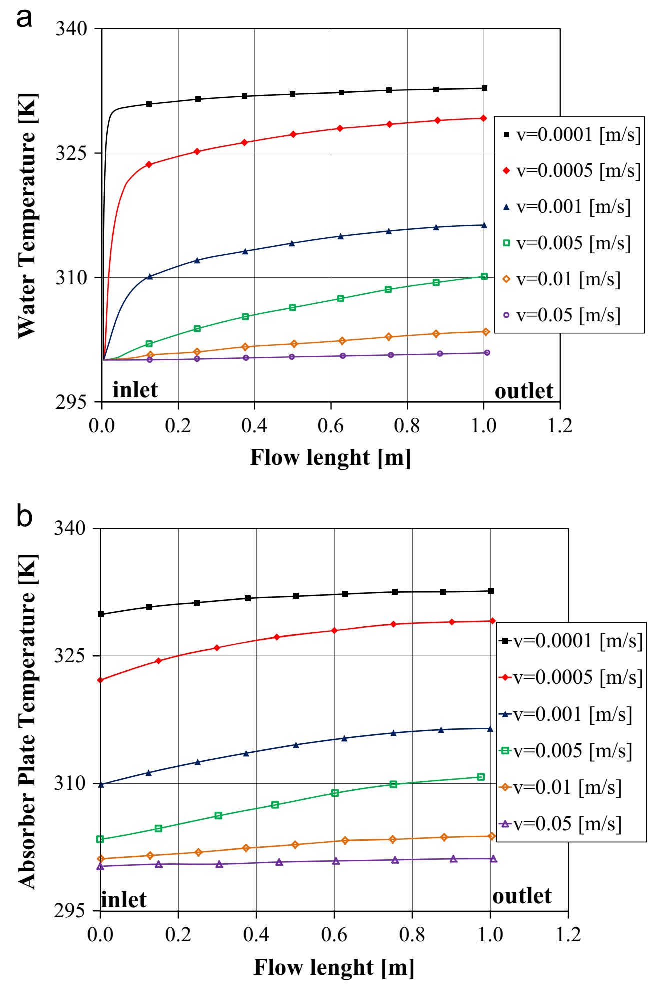

Fig. 9. Absorber plate (a) and water temperature (b) plot at different flow rate conditions obtained in [1].

Basavanna and Shashishekar [93] investigated the thermal performance of a flat-plate thermal solar collector with triangular tubes using Ansys Fluent 13®, showing that this configuration rises the outlet temperature thanks to a better contact at the interface between tubes and absorber plate.

A lot of CFD analyses have been conducted to investigate an Integrated Collector Storage Solar Water Heater system, ICSSWH [94,95]. This system integrates the flat-plate thermal solar collector and the hot storage water tank in a unique component. This embodiment can be classified into two basic categories: (i) a direct configuration (Fig. 10a), in which the service water flows directly in the storage inside of the solar collector, and (ii) an indirect configuration (Fig. 10b) in which several tubes are immersed inside the energy storage in the solar collector, with the service water flowing inside them. Both configurations reduce the cost of the entire system (no connection pipes between the collector and the water storage) and require a smaller area for installation [96]. In this context, Gertzos and coworkers [97–99] performed many experimental setups and CFD simulations in order to analyze the thermal behavior and the optimal design for both direct and indirect ICSSWH. The numerical analyses were conducted in 3D complex geometry adopting different CFD models implemented in the commercial CFD software Fluent 6.3®.Several configurations were analyzed, including the possibility to use water mixing in the storage by means of recirculation pumps. The comparison between the temperature profiles of two transient simulations and the relative experimental data showed a good agreement.

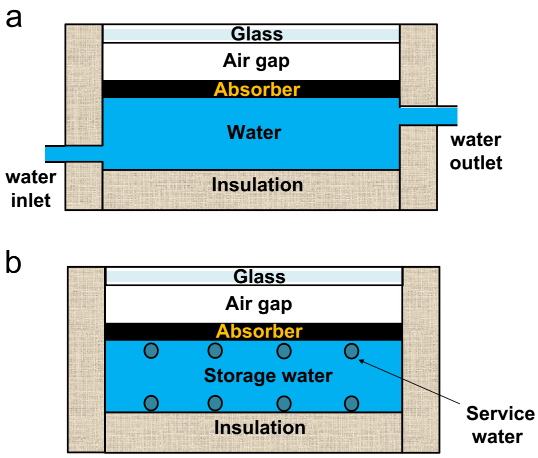

Fig. 10. Direct (a) and indirect (b) ICSSHW systems (adapted from [100]).

Finally, with the aim of increasing the thermal performance of ICSSWHS systems, Mossad and Al-Khaffajy [100] investigated two different configurations (single and double row inside the collector with two different diameters for the configuration b) adopting a steady 3D CFD approach. The results showed that the double row configuration, as shown in Fig. 10b, is not a good design because of the high cost and high pumping power required, with no additional benefits if compared to the single row configuration.

8. Conclusions

A review of numerical dynamic models and CFD analysis for flat-plate thermal solar collectors is presented in this paper. The main purposes of these different tools can be summarized as follows:

- to perform simplest and less expensive outdoor tests in situ in order to quantify the thermal characteristics of solar collectors and their main performance parameter η_{sc};
- to obtain simulation tools able to predict the energy yield of the solar thermal collectors with low computational costs;
- to realize regulation criteria for control systems in order to optimize the energy yield during operations in any working conditions (environmental, irradiance, user load, and so on);
- to analyze the solar collector in details to optimize its configuration from a design point of view.

These purposes given, the steady state model turns out to be an easy computational model, efficient and adequate to predict the energy yield of the solar collector as far as a long-time averaged performance (e.g., monthly) is required. In this sense, it is suitable for feasibility studies and for preliminary system design. Moreover, the steady state approach has a good performance also in the short-period (e.g., daily), only if the variations of the climatic conditions (mainly the solar radiation) are smooth. In the other cases the dynamics affects the panel behavior and the daily energy yield could be overestimated. Finally, testing the solar collectors in steady state conditions is complicated if only in situ outdoor experiments are feasible. Indoor tests are usually preferred despite their higher costs.

The transient lumped model is able to reproduce the dynamic behavior introducing an overall thermal capacitance of the whole solar collector. By adding further capacitance nodes for glass cover, fluid and back insulation, it is possible to increases the model capability in predicting the energy yields. This approach appears to be reliable for constant water inlet temperature and if the simulation time steps are suitably smaller than the characteristic time scale of the collector. On the other hand, the substantial inability in reproducing the spatial temperature profile inside the collector can cause errors in the outlet water temperature calculation. In any case, the lumped model is easy to be implemented and it does not require a great computational effort, making it suitable for testing procedure, simulation tools and control criteria in complex systems.

Thanks to the discretization of the solar collector, the 1*n-node* model is able to reproduce the temperature profile along the fluid flow direction and it permits a more accurate calculation of the outlet fluid temperature. Moreover, adding the discretization of glass cover, fluid and rear insulation, it is possible to increase the model accuracy, obviously increasing the computational cost. Thanks to their details, these models can reproduce the thermal performance of the solar collector also in presence of strong variations in the operating conditions and are therefore particularly recommended for outdoor in-situ performance tests of solar panels. Moreover, they are still sufficiently fast to be used for control purposes.

More complex models, in 2D and 3D geometries, can be physically rigorous but their implementation becomes difficult and unsuitable in a regulation control system perspective, owing to their computational costs. On the other hand, these complex approaches are suitable for detailed analysis of the heat transfer behavior inside the solar collector, in order to optimize the component design and construction. In this context the CFD analysis has demonstrated can be used productively to enhance the solar collector efficiency, e.g. searching optimized tube configurations, especially for particular equipment (i.e., ICCSWHS, PVT, nanofluids, etc.). Despite that, the main limitations of CFD are due to the slow computational speed and to the complexity of implementation, which also often requires commercial software.

The Artificial Neural Network (ANN) approach is a useful tool to be adopted in complex systems for control and optimization criteria, thanks to their conceptual simplicity and calculation speed. Moreover, their “auto-learning” ability makes these models adaptable also after changes or failures of the plant, by performing an on-line recalibration by means of new experimental data. However, the need of calibration makes this approach limited to each specific plant, so that it can be applied for predicting purposes only for the specific system and external conditions for which the model was calibrated.

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